Indications on self mode-locking in a broad area single-section quantum dot laser

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Abstract. Broad-area edge-emitting monolithic mode-locked semiconductor quantum dot lasers emitting at 1.26 μm could potentially serve as ideal sources for the generation of high power broad optical frequency combs for short-reach inter and intra data-center links. In this contribution, the inter-mode beat frequency of a 2 mm long InAs/InGaAs quantum dot laser with a broad-ridge waveguide are studied experimentally. Laser output power, radio-frequency and spectral domain analysis is performed. -3 dB spectral widths ranging from 2 nm to 5.3 nm and the existence of an inter-mode beat frequency at 20.4 GHz with a signal-to-noise ratio from 2 dB up to 11 dB are experimentally confirmed for injection currents from 0.225 A to 1 A. Our results indicate a potential way towards high output power optical frequency comb generation by electrically injected monolithic semiconductor lasers.

1. Introduction

Self mode-locked or frequency-modulated operation of near-infrared and mid-infrared edge-emitting semiconductor lasers allow for the generation of optical frequency combs [1, 2, 3]. In contrast to amplitude-modulated comb formation by passive mode-locking of two- or multi-section semiconductor lasers, the longitudinal modes generated by single-section Fabry-Pérot semiconductor frequency comb lasers are phase-locked without the need for a saturable absorber, or any active optical or electrical modulation and a continuous wave laser emission is generated. As an initial indicator for the coherence among the lasing modes, the appearance of a inter-mode beat signal and a threshold behavior of the inter-mode beat frequency line width suggests self-locking of the longitudinal modes due to internal non-linear effects as experimentally and numerically studied recently for a single-section narrow-ridge InAs/InGaAs quantum dot laser [4]. Above lasing threshold at a certain gain current, multi-modal emission switched from uncorrelated modes to self locked modes, corresponding to a reduction in inter-mode beat frequency line width and integrated intensity noise. The peak signal-to-noise ratio of the inter-mode beat frequency or pulse repetition rate is considered as one of the indicators of mode locking in two or multi-section semiconductor lasers [5]. The underlying physical effects causing self mode-locking or frequency modulated comb generation are yet to be fully understood although a fundamental role is played by four-wave mixing [1, 2, 6, 7, 8, 9, 10, 11]. Yet, the existence of an inter-mode beat frequency signal of a broad-area semiconductor laser and its evolution with biasing conditions, indicating self mode-locked operation and thus optical frequency comb formation, has yet not been reported.

2. Quantum dot broad area laser and experimental set-up

The investigated single-section broad-area quantum dot laser consists of 10 layers of InAs/InGaAs quantum dots separated by GaAs barriers. A light microscope picture is depicted in the inset of Figure 1(a). The waveguide width is 50 μm and both facets are left as-cleaved leading to a reflectivity of around 32 %. The total laser length is 2 mm corresponding to a free spectral range of 20.4 GHz. The laser is mounted on a copper cooling block and temperature stabilized at 21°C. Following light collimation, the laser emission passes an optical isolator (>60 dB isolation ratio) to prevent unwanted optical feedback. Then, the light is fiber-coupled and optical spectra are acquired with an optical spectrum analyzer (spectral resolution: 10 pm). Radio-frequency domain measurements are carried out by a direct detection technique consisting of a fast photo-diode (electrical bandwidth: 45 GHz) and an electrical spectrum analyzer (electrical bandwidth: 50 GHz). The emitted average optical output power is measured by a power meter.

3. Experimental results and discussion

The laser output power characteristics is depicted in Figure 1 for increasing (blue) and decreasing (green) gain injection currents indicating the absence of an optical output power hysteresis. The lasing threshold amounts to 0.13 A (0.13 kA/cm^2) and a slope efficiency of 0.19 W/A is indicated. An exemplary optical spectrum centered at around 1260 nm is depicted in Figure 1(b) for a gain injection current of 0.875 A (0.875 kA/cm^2). At this operation point, the -3 dB optical spectra width corresponds to 5.33 nm covering 50 optical modes.

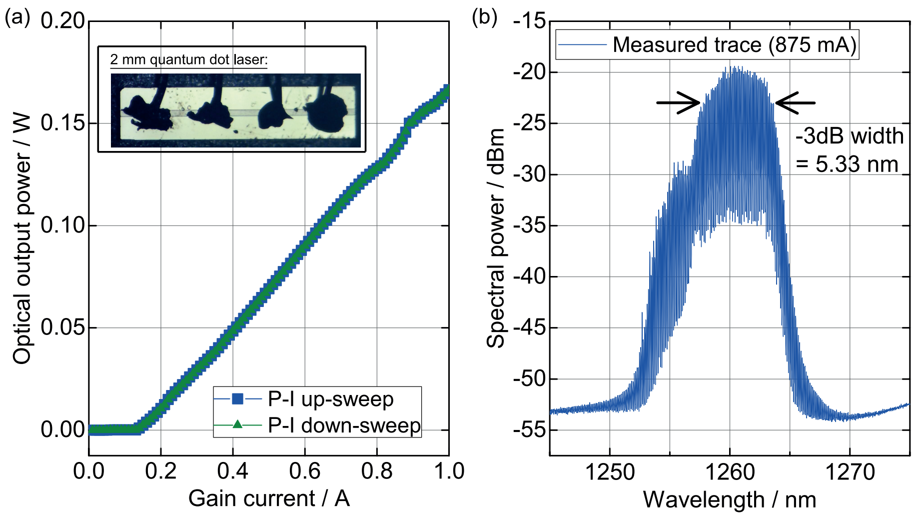

Figure 1. (a) Light output power characteristics of the broad-area quantum dot laser. The inset shows a light microscope picture of the laser. (b) Measured optical multimodal spectrum at a gain current of 0.875 A depicting a -3 dB width of 5.33 nm.

An exemplary full-span radio-frequency spectrum is depicted in Figure 2(a) for a biasing current of 0.875 A. A strong radio-frequency beat note signature denoting the inter-mode beat frequency is apparent at 20.4 GHz with a signal-to-noise floor ratio of 11 dB. The evolution of the inter-mode beat frequency peak signal-to-noise floor ratio is depicted in Figure 2(b) in dependence on the gain injection current. Up to an injected gain current of 0.2 A, the

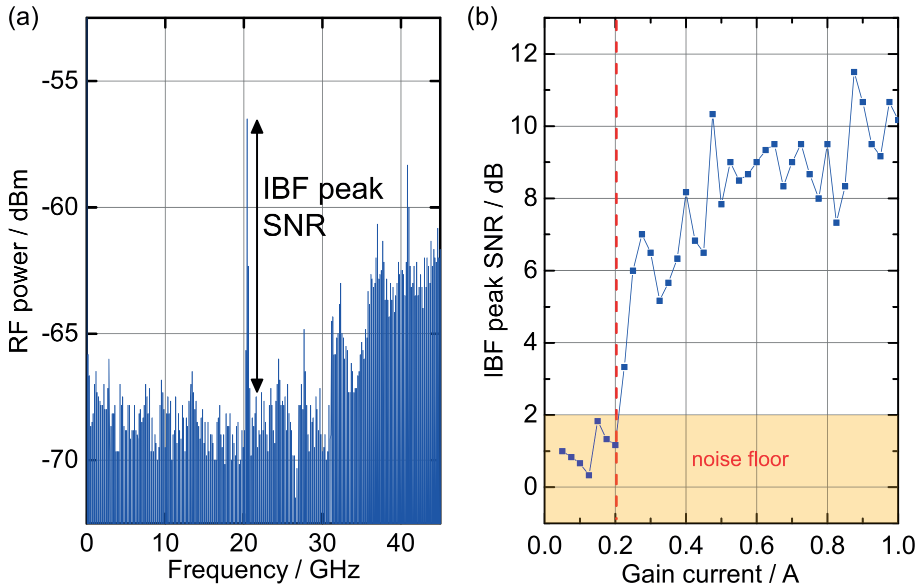

Figure 2. (a) Radio-frequency spectrum of the broad-area quantum dot laser exhibiting an inter-mode beat frequency (IBF) at 20.4 GHz with an inter-mode beat frequency peak signal-to-noise floor ratio (SNR) of 11 dB at a gain injection current of 0.875 A. (b) Inter-mode beat frequency signal-to-noise ratio in dependence on the gain injection current indicating the presence of strong beat frequency beat notes above 0.2 A.

inter-mode beat frequency is below the noise floor of the measurement instrument. For gain injection currents above 0.2 A however, strong inter-mode beat frequencies up to 11 dB of inter-mode beat frequency peak signal-to-noise floor ratio are recovered. The existence of such a threshold behavior in inter-mode beat frequency peak power has also been found experimentally in narrow-ridge quantum dot lasers and corresponding line width and noise characteristics have been linked to self mode-locking operation of a 1 mm long narrow-ridge single-section quantum dot laser [4, 2]. Figure 3(a) depicts the colour-coded optical spectra evolution in dependence on

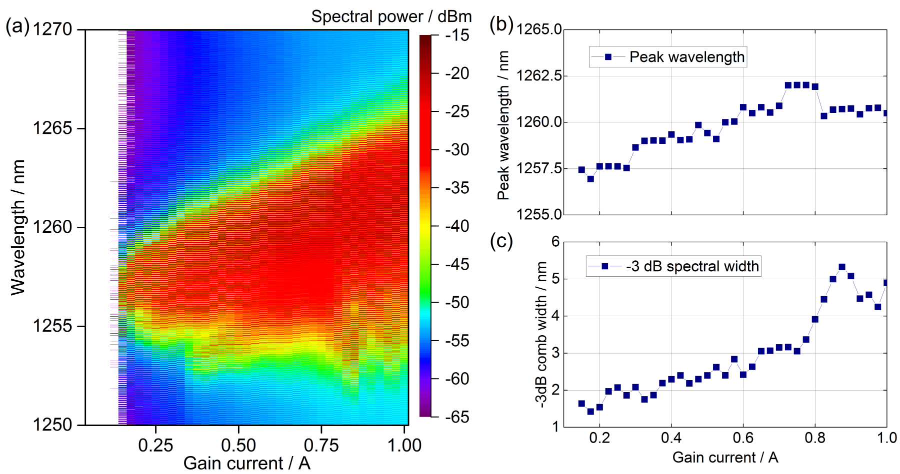

Figure 3. (a) Colour-coded optical spectra evolution in dependence on the gain injection current. (b) Peak center wavelength and (c) -3 dB spectral width.

the gain injection current in biasing current steps of 25 mA. The emitted multimodal spectra are centered at around 1260 nm. Figure 3(b) depicts the recorded emission wavelengths of the optical mode in the optical spectrum with highest spectral power as a function of applied gain current. A red-shift of the peak wavelengths with increasing gain injection currents by 4.7 nm/A are obtained. The -3 dB spectral widths of the optical spectra emitted by the broad-area quantum dot laser are presented in Figure 3(c). With increasing gain injection current, the optical spectral width increases up to a maximum value of 5.33 nm covering 50 optical lines.

4. Conclusion

We have experimentally studied the radio-frequency and spectral emission characteristics of a 2 mm long edge-emitting Fabry-Pérot monolithic InAs/InGaAs quantum dot laser with a 50 μm broad-area waveguide. For injection currents up to 1 A, the laser emits multi-modal emission centered at 1260 nm and with -3 dB spectral widths ranging from 2 nm to 5 nm, covering up to 50 modes. At injection currents below 0.225 A, the inter-mode beat signal is below the noise floor of the measurement equipment. Starting at an injection current of 0.225 A and up to 1 A, a sharp radio-frequency signature at 20.4 GHz, the inter-mode beat frequency, has been observed. A corresponding threshold behaviour has recently been found experimentally in narrow-ridge quantum dot lasers and related inter-mode beat frequency line width and intensity noise threshold characteristics had been associated to a transition from uncorrelated modes to self locked mode. Within the injection current range investigated in this contribution, the inter-mode beat frequency peak signal-to-noise ratio increased from 6 dB up to 10 dB. This threshold behaviour with increasing injection current suggests an initial indication for self mode-locking or frequency modulated comb generation in broad-area quantum dot lasers. Future studies will focus on the injection current dependence of the inter-mode beat line widths.

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